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Environmental Performances and Energy Efficiency for MSW Gasification Treatment

Deborah Panepinto · Vita Tedesco · Enrico Brizio · Giuseppe Genon

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Abstract For the final treatment of municipal solid waste (MSW), thermal disposal by incineration is the dominant technology to obtain energy from the material. In recent years, pyrolisis and gasification technologies have emerged, with the aim to increase energy output and to reduce environmental impact. While biomass pyrolisis and gasification are well known systems and technology of biomass gasifiers is sufficiently advanced, large scale MSW plants—characterized by high gasification efficiency and high energy recovery—are not so widespread. It must be considered also that MSW gasification can be cost competitive in comparison with combustion, besides the potential for better environmental performance. The purpose of this study is, after an analysis of the state of the art of this technology, to compare combustion process with pyrolisis/gasification process, by analyzing the following aspect: feasibility, waste gas emissions and energy recovery. The main results obtained highlight that gasification can be considered a really competitive technological alternative to incineration. From the point of view of the energy efficiency, the direct combustion of MSW seems to grant higher power productions if compared to syngas recovery. Only co-firing of syngas in large power plants or the use of combined cycle gas turbine might give better energy efficiency results, anyway the use of gas engine and gas turbine for syngas recovery could allow very good fuel utilization rates. With regards to air emissions, plants based on all the technologies in connection with a conventional steam boiler and steam turbine cycle can largely meet the emissions limits.

Keywords Energy performances · Environmental performances · Gasification technology · Incineration technology · Tar removal

D. Panepinto (✉) · G. Genon
DIATI, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Turin, Italy
e-mail: deborah.panepinto@polito.it

G. Genon
e-mail: giuseppe.genon@polito.it

V. Tedesco
ATO-R, Via Pio VII, 9, 10135 Turin, Italy
e-mail: vita.tedesco@atorifiutitorinese.it

E. Brizio
ARPA Piemonte, Via Vecchia di Borgo, 11, 12100 Cuneo, Italy
e-mail: e.brizio@arpa.piemonte.it

Introduction

The gasification and pyrolysis treatment of solid materials are not a new concept. Both these technologies have been extensively used to produce fuels such as coke and town gas for hundreds of years.

Large scale gasification units used by the petrochemical and power industries have several hundred installations worldwide. The characteristic of these systems typically is very high temperatures (1,100 °C and higher), short residence time and extremely rapid conversion of material in the gasification zone, very careful feedstock preparation by means of crushing and sieving the feed with a very carefully controlled moisture content.

It is evident that the characteristics of municipal solid waste (MSW) (inconstant on size and moisture content and highly variable on heat caloric value) do not easily fit these demands. Heat and mass transfer dynamics between a selected feed as fluff, plastic, biomass or MSW are very

different and feedstock preparation could exceed the economic parameters [1–7].

Today the main difficulties to apply the principles of gasification to MSW seem to be solved and gasification could be a reliable solution for waste disposal: there are in fact as many as 100 plants around the world that use gasification systems to process MSW.

One of the potential benefits of gasification is that the syngas can be used not only to produce steam that can be used to generate electricity by a steam turbine, but also to feed a dedicated gas engine or a gas turbine; in addition to using the syngas to produce energy, it can also be used as a chemical feedstock.

This report investigated several facilities for gasification of MSW all over the world in order to evaluate the environmental and energetic issues spotlighting the pros and cons of this technology, the development opportunities and the open problems.

Materials and Methods

Processes and Technologies for Gasification

The gasification and pyrolysis treatment for a homogeneous flow of a solid fuel is a well established technology in industrial applications: it could be applied to heterogeneous flows, but in this case some specific aspects must be considered (feed composition, physical state, thermotechnical characteristics) [8–14]. In this paper we studied this last case.

From the point of view of plant, there are several constructive solutions operating on the market [10], which must be carefully evaluated. The produced syngas must be destined to energetic uses in combustion plants (for the moment we do not considered more attractive but today not currently technologically mature options for innovative use, as production of chemicals, use in fuel-cells, production of grid immitted methane). About energetic use, the choice of the particular solution for combustion operation determines the syngas pretreatment necessity, the energetic yield of the production scheme and the quality of emissions. The first of the above mentioned topics decidedly requires difficult operations, in account of the very high presence, multiplicity and complexity of pollutants (dust, tar, acid gases) that must be removed; on the other hand this operation is fundamental in order to arrive to solutions of particular efficiency as concerns the energetic utilization (internal combustion engines, gas turbine systems), as an alternative to traditional solutions, today the most used (combustion in boiler with coupled steam cycle or Organic Rankine Cycle—ORC); from gross yields of 28–31 % of conventional systems it is possible to arrive to 37–41 % with alternative engines, and up to 50 % with gas turbines in combined cycles. It is fundamental to evaluate the aspect of quality of emissions from the thermal system; reliable informations on the levels of pollutants (mainly dust, NO_x, CO) in different configurations are available. The definition of the potential environmental impact is, in addition to the aforementioned aspect of energy production, a fundamental aspect of the evaluation.

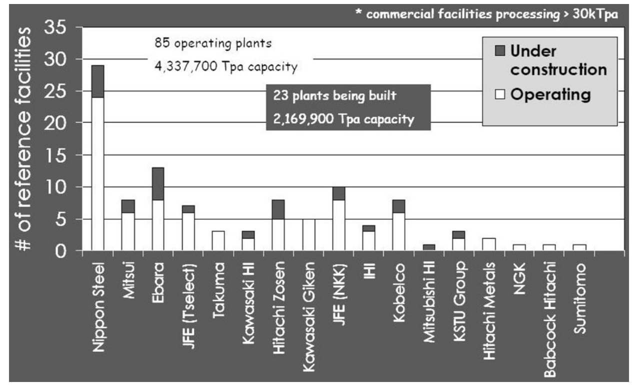

Fig. 1 Gasification infrastructures in Japan (Juniper Database)

Gasification: State of the Art

Gasification and pyrolysis have been applied to waste treatment since 1970s, but the application of these technologies to MSW has not found, so far, a world-wide diffusion except for Japan, where a lot of innovative plants have been built, generally based on the gasification process and, on a small scale, on the pyrolysis. In other countries (in particular USA, United Kingdom and Italy) the possibility to resort to innovative technologies of heat treatment for MSW started to be considered recently. In 2007 in Japan there were 85 operating gasification plants with an average capacity of about 200 t/day of waste and a maximum capacity of 720 t/day (Fig. 1). The main plant configurations in Japan are the following ones:

- gasification in a vertical shaft furnace and melting section for ashes (Nippon Steel, JFE NKK, Kawasaki HI, Sumitomo);
- fluidised bed gasification (Ebara, Kobelco Eco Solutions, Hitachi Zosen, Kawasaki HI);
- pyrolysis in rotary kiln and melting (Mitsui, Takuma, Babcock Hitachi, Mitsubishi HI, IHI);
- pyrolysis and high temperature gasification (Thermoselect, JFE);
- plasma gasification (Hitachi Metals).

In Europe there are few industrial applications of pyrolysis and chiefly gasification technology (Norway, Germany, England and Iceland). The Techtrade process is based on low temperature pyrolysis of the MSW: there is a

Table 1 Ten greatest gasification/pyrolysis plants of MSW in the world

Plant	Capacity	Supplier	Start date	Technology
SVZ, Germany	250,000	Envirotherm	2001	Gasification + melting
Shin Moji, Kitakyushu City, Japan	220,000	Nippon Steel	2007	Gasification + melting
Ibaraki, Japan	135,000	Nippon Steel	1980	Gasification + melting
Aomori, Japan	135,000	Ebara	2001	Gasification + combustion + melting
Kawaguchi, Japan	125,000	Ebara	2002	Gasification + combustion + melting
Toyohashi, Japan	108,000	Mitsui	2002	Pyrolysis + combustion + melting
Akita, Japan	120,000	Nippon Steel	2002	Gasification + melting
Oita, Japan	115,000	Nippon Steel	2003	Gasification + melting
Chiba, Japan	100,000	Thermoselect	2002	Gasification + melting
Hamm, Germany	100,000	Techtrade	2002	Pyrolysis + combustion

small plant (40,000 t/year) in Burgau in Germany, based on this technology, which has been in operation for more than 25 years and a new plant at Hamm with a capacity of 100,000 t/year. Energos has several significant gasification plants in Norway and one in Germany; however, these plants are relatively small (10,000–30,000 t/year with one plant having a capacity of 70,000 t/year). Energos proposes a thermal conversion that takes place in two stages: gasification of the waste in the primary chamber equipped with a fixed horizontal grate and oxidation of syngas in the secondary chamber. Concerning high temperature gasification it is important to highlight the negative experience of the Thermoselect plant at Karlsruhe, in Germany (200,000 t/year), started in 1998 and closed down in 2004, after spotlighting significant technical problems. However in Japan there are six gasification plants based on Thermoselect technology; these plants treat MSW and seem to have been in successful commercial operation since several years.

In Italy there are no innovative technology plants treating MSW but only plants of small size treating waste as refuse of paper-mill, biomass (olive husk, wood, etc.). The only exception is the gasification plant of Rome Malagrotta, started in August 2008, with a potential capacity of 500 t/day of RDF (Refuse Derived Fuel). During 1990s three demonstrator/commercial plants for MSW (in Verbania, in Greve in Chianti and in Porto Azzurro) have been constructed, but none of these plants is still operating.

In spite of the Italian negative experience in MSW gasification, the innovative plants operating in the world have demonstrated a good technological and environmental reliability, above all for the medium size. The Table 1 reports the ten greatest gasification/pyrolysis plants of MSW in the world; it shows the presence of mean-large size plants nearly exclusively in Japan.

In the following chapters we report some details of the most well-known innovative technologies applied to MSW.

Gasification: Environmental and Energy Performances

In order to gather information on pyrolysis and gasification technologies a bibliographical research has been carried out over several sources.

In the present study it was decided to consider all the technologies for the treatment of MSW that Juniper has defined as “proven” and “fully proven” and for which it has been possible to find sufficient technical, economic and environmental informations. These technologies are reported in Table 2. In particular the Table 2 reports the Company that developed the process, the process (gasification, pyrolysis or plasma), the capacity of the plants, the feed (kind of used refuse), the number of working plants existing in the word and the date of plant start.

Environmental Issues

The Tables 3 and 4 report the main emission parameters (Table 3) and the amount of solid residues (Table 4) of some technologies considered in the study.

The pollutants level in the raw syngas can be lower than the level in the flue gas of a traditional incinerator (for example the low levels of oxygen present in pyrolysis and gasification processes could inhibit the formation of dioxins and furans), but this aspect doesn’t correspond directly to an advantage for the innovative technologies; in fact in pyrolysis/gasification plants energy is produced by the combustion of raw syngas produced in a steam boiler without treatment and this option does not differ very much from incineration; final product is a gas that should be treated before its discharge to atmosphere through a stack.

Table 2 Selected companies (in alphabetical order)

	Company	Process	Capacity of working plants (t/year)	Refuse	Number of working plants	Start date (first–last plant)
1	AlterNRG (Canada), Westinghouse Plasma Corporation, Hitachi Metals (Japan)	Plasma	8,000–90,000	MSW, RDF, ASR, tyres	2 + 1 under construction in USA (1,000 t/day)	2002–2002
2	Compact Power (UK)	Pyrolysis and gasification	8,000	HW	1	2002
3	Ebara TIFG (Japan)	Gasification	34,000–180,000	MSW, IW	8	2002–2007
4	Energos (Norvegia)	Gasification	10,000–75,000	MSW	7	1997–2009
5	Enerwaste International Corporation EWOX (USA), Planet Advantage (UK)	Gasification	500–40,000	MSW	8	2005–2008
6	Entech (Australia), IET Energy (UK)	Gasification	5,000–20,000	MSW	8	1991–2006
7	Mitsui (Japan), Takuma (Japan)	Pyrolysis and combustion	50,000–108,000	MSW, ASR	6	2000–2008
8	Nippon Steel (Japan), Paul Wurth (Italy)	gasification	30,000–230,000	MSW, IW	28 + 8 under construction	1979–2008
9	PKA (Germany)	Pyrolysis and gasification	12,000–27,000	MSW, IW	2	1999–2000
10	Plasco energy (Canada)	Gasification and plasma	28,000	MSW	1	2007
11	TechTrade (Germany), Wastegen (UK), Icom (Italy)	Pyrolysis	40,000–110,000	MSW, sludge	2	1987–2002
12	Thermoselect (Switzerland), IWT (USA), JFE (Japan), 7 Hills (Switzerland)	Pyrolysis and gasification	30,000–200,000	MSW, IW	7	2002–2006
13	Thide Environment (France)	Pyrolysis	10,000–70,000	MSW, IW	3	2002–2004
14	Tpf Basse Sambre (Belgium)	Pyrolysis and gasification	12,000	MSW/RDF	1	2003

MSW municipal solid waste, *RDF* refuse derived fuel, *ASR* auto shredder residue, *HW* hospital waste, *IW* industrial waste

As far as exhaust gas volume (tightly linked to waste lower heating value, therefore to the carbon content), "gasification" (generally understood as all types of processes that result in the generation of a syngas) produces volumes of flue gas lower than those from conventional incineration for the intrinsic stoichiometric characteristics of the process. In fact, while some amount of excess air above stoichiometric requirements is needed for the complete combustion of the waste, pyrolysis takes place in the absence of air, gasification by carefully controlling the amount of oxygen (or other gasificant agent). Since in a steam cycle the combustion of produced syngas takes place in a steam boiler with air addition, pyrolysis/gasification process leads to a two stages incineration, so the amount of exhaust gas to be sent to cleaning equipment is comparable to that of the traditional combustion (Table 3), in terms of volume produced for ton of treated waste (6,000–7,000 Nm^3/t).

From the point of view of the sludge material (Table 4) the high temperature gasification processes (Thermoselect, Nippon Steel, Ebara, Hitachi Metals, etc.) produce a vitrified slag with low leaching characteristics. It may be transported to landfill or recovered (i.e. in road construction) depending on local standards, reducing the cost of disposal (Table 5).

Energetic Performances

An incinerator for MSW is made up of the following main items: a furnace, an afterburning chamber, a heat recovery steam generator and the emission control equipment. After the post-combustion chamber, the exhaust gas enters the heat recovery boiler, where steam is produced. Steam can be used for industrial usage, for district heating or for energy production in a steam turbine. State-of-the-art technologies can achieve net electric efficiencies up to about 22–25 %.

Syngas is a combustible gas product and represents a more flexible form of energy than hot combustion gas. In fact syngas can be used immediately adjacent to the place of production or can be piped to a location remote from the site of production; moreover the syngas can be burned in a boiler to produce steam and electricity or it can be used as a fuel in reciprocating engines, combined cycle turbines and

Table 3 Air emissions from some technologies considered

Company		Flue gas (Nm^3/t)	mg/Nm^3								PCDD/PCDF ($\mu g/Nm^3$)
			Dust	HCl	HF	SO_2	NO_2	CO	Hg	Cd + Tl	
AlterNRG	PL	1,400–2,400	<3	22–39		<1–2	62–82	<29			0.00059–0.00067
Compact Power	P + G		1.4	0.96	0.12	0.74	21	3.9		0.006	<0.003
Ebara	G	2,952	<1	2		<2.8	29.3		<0.005		0.000051
Energos	G	7,894 Nm^3/t lhv 10.8 MJ/kg	0.2	3.6	0.02	19.8	42 (without deNOx)	2	0.00327	0.00002	0.001
Enerwaste	G			0–6.5		16.6–25.4	58.7–199.2 (without deNOx)	30.9–40.5			
Mitsui	P + C		<1	9		8	150	5	0.01	<0.001	0.016
Nippon Steel	G	5,760 lhv 8.4 MJ/kg	6	3		0.5	16	5.2			0.023
TechTrade	P	6,495 lhv 8.5 MJ/kg	0.3–1.8	5.5–6.4		5.42	179.5	5.65	0.0066–0.0117	0.0006	0.0013
Thermoselect	P + G		0.2	<5			14				0.0072
Tpf Basse Sambre	P + G	5,600 lhv 12.5 MJ/kg	2.8	9.3	0.12	11.1	327 (now 200 without DeNOx)	7.4	0.00013	0.0011	0.06
D. Lgs. 133/2005			10	10	1	50	200	50	0.05	0.05	0.1
BAT			1–5	1–8	<1	1–40	40–100	5–30	<0.05	0.005–0.5	0.01–0.1

Reported values to dry gaseous effluent to 0 °C, 1 atm., 11 % O_2

lhv lower heating value, *G* gasification, *P* pyrolysis, *Plasma* plasma gasification

Table 4 Amount of solid residues from some technologies considered

Company		Solid residues		
		Typology	Amount (% on waste IN)	TOC (%)
AlterNRG	PL	Slags	5–6 %	–
Ebara	G	Slags + inerts	6.7 (recyclable) + 6.1 (to landfill)	–
Energos	G	Bottom ashes	7–20 %	1
Mitsui	P + C	Slags	7	–
Nippon Steel	G	Slags	9–10 %	–
Plasco energy	G + PL	Slags	9–15 %	
TechTrade	P	Coke	53 %	26
Thermoselect	P + G	Slags	7–13 %	–
Thide Environment	P	Coke	24 % (project data)	50
Tpf Basse Sambre	P + G	Bottom ashes	13 %	<3

C combustion, *G* gasification, *P* pyrolysis, *PL* plasma gasification

also eventually in hydrogen fuel cells to obtain higher conversion efficiency. As far as the potential for fuel cells to generate energy from hydrogen (power conversion efficiencies exceeding 40 %), in reality very little research has been carried out on the use of syngas derived from MSW in hydrogen applications and they are presently unlikely to attract commercial finance. The Integrated Gasification Combined Cycle (IGCC), based on the combination of a gasification system with a gas turbine and a steam cycle, has the potential to achieve power conversion efficiencies exceeding 40 %. The maintenance of the gas turbine is critical for the success of the IGCC because the IGCC turbine's lifetime can be limited due to erosion and high temperature corrosion caused by impaction of particles and deposition of impurities such as alkali metals in the product gas. Also running dedicated gas engines or gas turbines on syngas requires cleaning and cooling prior to use, but syngas cleaning systems are very complex and today some practical problems still persist. For this reason the most common configuration is to burn the syngas in a boiler to generate steam (e.g. Energos process); in fact the steam cycle is the simplest option for energy recovery because it does not need gas pre-treatment (tar is burned in the combustor and it cannot damage the boiler).

In Japan less than 10 % of gasification plants produce energy by high efficiency systems after cleaning syngas. The only example of IGCC on syngas is the gasification plant SVZ in Schwarze Pumpe (Germany), on which however it has not been possible to acquire information of greater detail.

Moreover alternative technologies show in general important internal parasitic energy demands in comparison with conventional incineration because of waste pre-treating (processing to remove excess moisture, shredding to reduce the size, etc.), use of pure oxygen as gasifying agent, etc.; internal energy demand grows considerably for the high temperature systems reaching 30–40 % of energy production (e.g. AlterNRG, Ebara, Nippon Steel); syngas cleaning also contributes to the increment of power consumption (e.g. Thermoselect).

Today's levels of conversion efficiency to electricity of innovative technology plants are similar, or even lower, in comparison with those of a typical solid waste incinerator (19–27 %) because energetic recovery systems normally adopted are based on typical steam cycle; syngas could be fed into gas engines, gas turbines or IGCC systems with better results but pollutants must be removed [15–18].

The TAR Problem

When MSW is gasified, significant amounts of tar are produced (between 0.1 and 10 % of the product gas) [19]. The amount and composition of tars are dependent on the fuel, the operating conditions and the secondary gas phase reactions [20].

If tar is allowed to condense (condensation temperatures range from 200 to 600 °C) it can deactivate sulfur removal systems, erode compressors, heat exchangers, ceramic filters, and damage gas turbines and engines.

Both physical and chemical treatment processes can reduce the presence of tar in the product gas. Wet physical processes work via gas tar condensation, droplet filtration, and/or gas/liquid mixture separation (cyclones, cooling towers, venturis, baghouses, electrostatic precipitators, and wet/dry scrubbers are the primary tools). The main disadvantage to using wet physical processes is that the tars are just transferred to wastewater, so their heating value is lost and the water must be disposed of in an environmentally acceptable way (wastewater that contains tar is classified as hazardous waste).

Table 5 Energy recovery from some technologies considered

Company		Reference plant	Electricity produced (MWh/t)	Electricity to National Grid (MWh/t)	Heat produced (MWh/t)	Heat to external users (MWh/t)	Net efficiency[a] (%)
AlterNRG (Canada)	PL	Utashinai, Japan	0.934	0.508			18.6
Ebara (Japan)	G	Project for New York	0.547	0.383			13–15
Energos (Norway)	G	Project data	0.750	0.625			18.5
		30,000 t/year; lhv = 12 MJ/kg					
Enerwaste (USA)	G	Project data	0.55				
Entech (Australia)	G	Project data	0.573				17
Nippon Steel (Japan)	G	Shin Moji, Japan	0.784	0.536			15.7
		194,000 t/year; lhv = 11 MJ/kg					
TechTrade[b] (Germany)	P	Burgau, Germany	0.214	0.059		0.056	2.9
		26,807 t/year; lhv = 8.5 MJ/kg)					
		Project data	Steam cycle: efficiency pre internal energy demands = 24.6 %				
		50,000 t/year; lhv = 14.6 MJ/kg	IGCC (in need of experimental tests): efficiency pre internal energy demands = 33.6 %				
			Gas engines (in need of experimental tests): efficiency pre internal energy demands = 38.3 %				
Thermoselect (Switzerland)	P + G	Theoretical value	1.03	0.705	1.39		19
		lhv = 12 MJ/kg					
Tpf Basse Sambre[c] (Belgium)	P + G	Keflavik, Iceland	0.200	0.140	–	–	4
		12,000 t/year; lhv = 12.5 MJ/kg					
		Project data	0.700	0.620	–	–	18
		30,000 t/year; lhv = 12.5 MJ/kg					

A new plant of 30,000 t/year and lhv = 12.5 MJ/kg, would allow to produce totally 0.7 MW/h/t with internal parasitic energy demands of 0.08 MWh/t

C combustion, *G* gasification, *P* pyrolysis, *PL* plasma gasification

[a] Ratio of the energy extracted from the waste as electricity after internal energy demands, divided by the energy content of the waste feedstock

[b] Data in the table refer to Burgau plant, started in 1987. A new plant of 50,000 t/year and lhv = 14.6 MJ/kg, according to the Supplier, would achieve electric conversion efficiencies pre internal energy demands of 24.6 % through the use of a steam cycle

[c] Keflavik plant was designed to produce hot water and then modified to produce electricity

Dry physical processes using ceramic, metallic, or fabric filters are alternatives processes. However, at temperatures above 150 °C, tars can become “sticky” causing operational problems; as a result, such dry tar removal schemes are rarely implemented. Injection of activated carbon in the product gas stream or in a granular bed may also reduce tars through adsorption and collection with a baghouse. The carbonaceous material containing the tars can be recycled back to the gasifier to encourage further thermal and catalytic decomposition.

Thermal destination tar processes are widely used in the gasification industry: in fact it has been shown that this process is able to break down aromatics at temperatures above 1,000 °C. However, such high temperatures can have adverse effects on heat exchangers and refractory surfaces due to ash sintering in the gasification vessel.

The most widely used and studied tar cracking catalyst is dolomite (a mixture of $MgCO_3$ and $CaCO_3$), employed downstream or also in the gasifier.

The oil based gas washing (OLGA) developed by ECN and Dahlman not only removes tars, but also dust as well as contaminants like thiophenes and dioxins from the product gas of a (biomass) gasifier [21–23].

As reported in literature [23, 24] the philosophy of OLGA is all about dew point control. In Fig. 2, the tar and water dew points are shown, together with the logical process steps. In OLGA, the tars are separated, first by

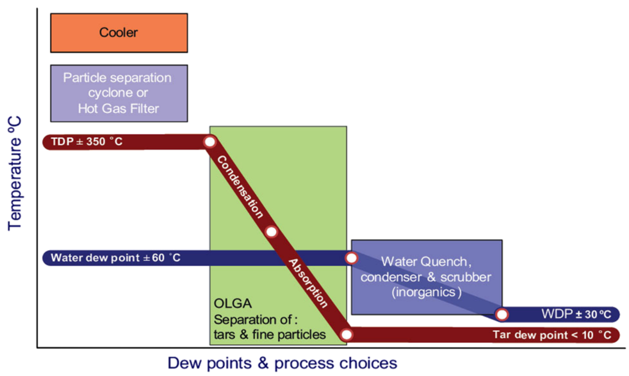

Fig. 2 Importance of the dew points for equipment selection

condensation of heavy tars by cooling the gas from just above the tar dew point of the gas to just above the water dew point and secondly by absorption of light tars. The key philosophy in this is operating OLGA above the water dew point, while decreasing the tar dew point to a level under the lowest process temperature. As such, conventional water-based scrubbing technologies can be applied without mixing water and tars.

The tar removal principle of OLGA is based on a multiple stage scrubber, as shown in Figs. 2 and 3, in which the gas is cleaned by special scrubbing oil. In the first section of OLGA (the collector), the gas is gently cooled down by the scrubbing oil. Heavy tar is condensed, is collected, and is separated from the scrubbing oil. The heavy tar condensate together with the fine solids is recycled to the gasifier as a liquid. In the second stage (the absorber/stripper), lighter gaseous tars are absorbed by the scrubbing oil resulting in a product gas practically free from tars and solids. In the absorber column, the scrubbing oil is saturated by these lighter tars. This saturated oil is regenerated in a stripper. This air used for stripping the absorber oil, hence loaded with light tars, is recycled to the gasifier for combusting and as fluidization medium [23].

The OLGA methodology allows to obtain a flue gas with a TAR residual concentration in accord with the standard required from the more performing apparatus.

Consideration on the State of the Art

In the following lines some considerations regarding the above mentioned state of the art are reported:

- gasification is the most complete and competitive technological alternative to incineration for the energetic valorization of the MSW;
- pyrolysis has been demonstrated to operate satisfactorily on specific feed material, like industrial waste, but today it doesn't constitute a complete alternative to the incineration of MSW, considered also the reduced number of systems in exercise on an international scale. The main problem remains the solid residue (sometimes described as a char): pyrolysis plants produce a bottom residue that contains significant amounts of carbon. The char needs an ulterior stage of treatment to reduce the carbon content; for example it could be used as coal replacement in certain combustion applications or as a gasifier feedstock (for systems based on the combination of pyrolysis and gasification);
- plasma torch can't be considered suitably proven due to a lack of adequate references on MSW treating;
- as the levels of contaminants in the raw syngas can be less than the raw gas of an incinerator, this aspects does not prefigure a direct environmental advantages, because the energy recovery of the syngas commonly realized, that is combustion without preventive purification, and the presence of a line of gas treatment similar to that of a conventional incineration plants to make that new technology plants present similar performance of a conventional incinerator in terms of quantity and quality (concentration of contaminants) of the exhaust fluxes;
- at present, the levels of energy recovery are similar, in some cases lower than those of an incinerator, because energy recovery normally used downstream of the waste thermal treatment is of conventional type (steam cycle) and it doesn't allow improvement of electricity production efficiency compared with traditional incinerator. The state of the art for the syngas purification technologies doesn't achieve the quality standards required by high performance equipment in terms of electricity production yield (for example gas turbine, Otto cycle engines).

Results and Discussion

Energy Comparison Between Incineration and Gasification

A comparison between incineration and gasification has been carried out as far as energy recovery is concerned, by using both literature data and specific evaluations. Based on several data from existing plants [25], it can be said that thermal conversion efficiencies for gasification/pyrolysis are in the range 55–75 %, maybe some more points in the case syngas is directly used in a steam boiler without any pre-cooling [26, 27].

As far as power generation is concerned the following typical electrical generation efficiencies can be taken into account for the different thermodynamic cycles:

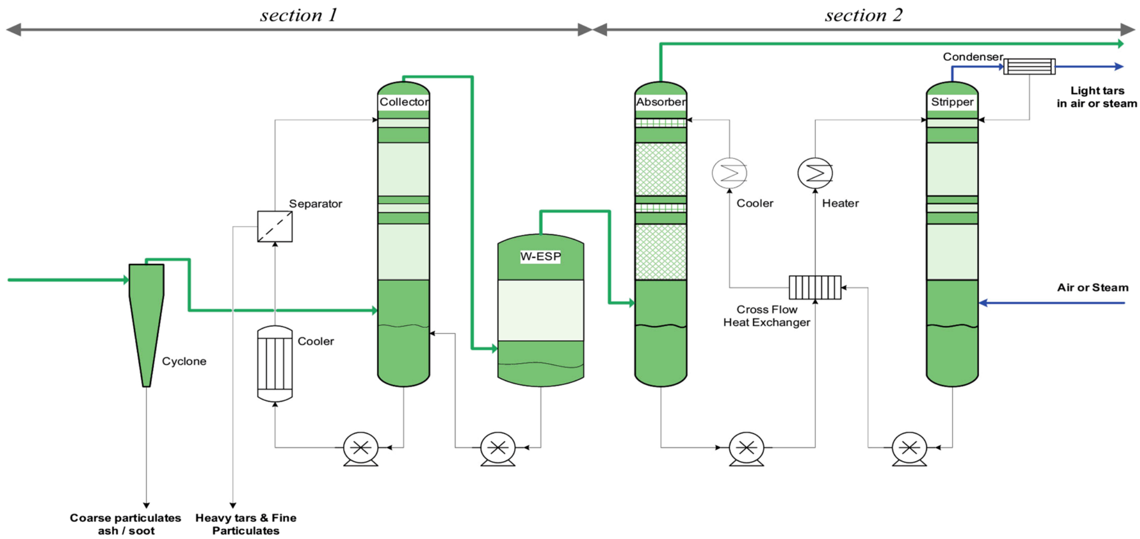

Fig. 3 Simplified process flow diagram of OLGA

- modern steam turbine systems (SC), size/temperature/pressure typical for MSW plants: 31 %;
- gas engines (GE): from 34 up to 41 %. At least the same amount of thermal energy can be recovered from engine cooling and waste gas;
- gas turbine (GT): for a small scale gas turbine, a net electrical efficiency around 30 % could be representative; at the same time, the thermal energy recovered from waste gas could be around 42 % [28];
- combined cycle gas turbine (CCGT): in this case, electrical generation efficiencies of large natural gas turbine (>55 %) cannot be considered representative for smaller scale gas turbine fed by a fuel gas with a lower calorific value. Fichtner Consulting (2004) suggests that a net generation efficiency around 41 % could be taken into account for a small scale industrial CCGT plant.

In the case pyrolisis/gasification uses steam cycles to produce power (see the literature data showed in Table 6), the net electrical efficiency is about 14–20 %, lower than the direct combustion process. When a gas engine is used to recover syngas chemical energy, the net electrical efficiency is around 13–24 %, that is even the use of the most efficient gas engines is not enough to reach higher efficiencies than those from direct incineration. Only the use of a combined cycle gas turbine might give better results (even more than 26 %) but the use of gas turbine for syngas is still largely unproven anywhere in the world whereas the use of gas turbine alone would give a gross electrical efficiency around 22 %.

The analyses carried out by the reported source is somehow partial as they don't take into account the potential thermal energy that could be generated by the different energy recovery processes. The produced thermal energy amount is very important as it could replace existing thermal plants and the relative emissions in order to improve the emissive balances and mitigate the impacts of the new waste-to-energy plant. Table 7 reports an attempt to quantify the overall fuel utilisation parameters for different technological solutions. The reported figures are drawn from general efficiencies that can be found in literature [29] and they underline that pyrolysis/gasification using gas engine and gas turbine could produce less power than direct combustion (in particular because of waste pretreatment requirements) but large amounts of thermal energy, at high temperatures too, can be generated and made available to self-consuming or third users without decreasing power production, marking out a fuel utilisation higher than 50 %. The last parameter could be even improved in the case syngas cooling is recovered (15 %). On the contrary, combined heat and power (CHP) from a steam cycle would strongly decrease power generation and this operating choice is usually less performed.

One of the most interesting options in order to increase energy production from pyrolysis/gasification is co-firing of syngas in conventional power stations or cement kilns. As a matter of fact, low efficiencies of standalone waste-to-energy plants are due to their relatively small scale. The

Table 6 Net electrical efficiencies claimed by technology suppliers [23]

	Combustion	Gasification and pyrolysis		
η Electric (%)	Steam cycle	Steam cycle	Gas engine	CCGT
	19–27	9–20	13–24	23–26

Table 7 Electrical and thermal efficiency for different waste-to-energy processes

	MSW combustion (%)	MSW gasification → gas engine (%)	MSW gasification → gas turbine (%)
Thermal conversion efficiencies	80	70	70
Power generation efficiency	31	38	30
Overall generation efficiency	25	27	21
Thermal generation efficiency	0	45	42
Thermal energy efficiency	0	32	29
Fuel utilisation	25	58	50

use of syngas as a substitute fuel could have the following advantages:

- no cleaning requirements before the use;
- no cooling before the use; as a consequence, the sensible heat of the syngas wouldn't be lost;
- no additional equipments required for syngas recovery;
- less capital costs and benefits from the economies of scale;
- replacement of fossil fuels;
- the char can be recovered in the conventional boiler [30];
- the net electrical efficiencies attributable to the gasification portion is claimed to be about 33–35 % [25].

Emissive Performances: Comparison Between Incineration and Gasification

As far as emissions of waste-to energy plants are concerned, in order to compare the atmospheric impacts of different processes it's important to define the mass flows expected for different pollutants, that is NO_x, particles, CO, metals, acid gases, micro-pollutants as for example dioxin. The first step is the definition of waste gas flows from the direct combustion of waste and from syngas energy recovery. The combustion of RDF usually produces a dry flue gas volume around 6,000–7,000 Nm^3/t RDF ($O_2 = 11$ %) whereas the definition of syngas production from pyrolysis/gasification is not straightforward and it strongly depends on operative conditions (air, oxygen, auto/allo thermal). Arena and Mastellone [31] reports that air gasification requires between 1.4 and 2.4 kg air/kg RDF, that is syngas is just 1/3 of the waste gas produced by traditional incineration (1/10 for oxy-gasification), with favourable consequences on cleaning equipments' general costs. Nevertheless, the stoichiometric waste gas volumes deriving from the combustion of the syngas, assuming that autotherm gasification is carried out in the best way (inert residues), should be more or less the same as that from direct combustion, that is 3,500–4,000 Nm^3/t MSW with a water content of waste gas ranging from 20 to 25 %. The real flue gas volumes depend on the excess air ratio, that depends on the chosen process: syngas could be recovered by gas engines or industrial boilers whit lower excess air if compared to traditional solid waste incineration (reference oxygen content at 11 %).

Table 8 figures out emissions to air of waste-to-energy plants using steam cycles, both for direct combustion of waste and syngas combustion after pyrolysis-gasification. All pollutant concentrations are corrected to WID (2000/76/CE) reference conditions of dry gas and 11 % oxygen.

All three types of technologies (combustion, gasification, and pyrolysis) can achieve emissions significantly lower than the WID limits.

Emitted pollutants can be divided into three main groups.

The first one, for example acid gases, has a stoichiometric evolution from the initial waste: differences in acid gas emissions are due to the flue gas treatment system, the input waste composition and the use of lime mixed to the waste, that is the choice of thermal treatment process (gasification, pyrolysis, or combustion) is not a significant factor in determining acid gas emissions as one can easily notice from the reported data.

The second group, metals and micro-pollutants, mainly depends on gasification conditions, that is temperature, oxygen content, residence time, catalytic activities of different substances. Generally, combustion processes operate at higher temperatures than gasification processes, which in turn operate at higher temperatures than pyrolysis processes. Lower operating temperatures and less vigorous chemical reactions mean that lower quantities of pollutants such as heavy metals are likely to be volatilised into the gaseous stream. Table 8 indicates that gasification and pyrolysis plants generally emit lower levels of dioxins and certain metals to air compared to combustion plants. The result is higher levels of pollutants in the char residue and lower levels of pollutants in the flue gas requiring removal in the flue gas treatment system.

The last group of pollutants (CO, NO_x, particulates) depends on the way syngas is recovered, that is combustion conditions (turbulence, time, temperature, air excess): the alternative thermal technologies based on syngas generation and combustion in industrial boilers offer the prospect

Table 8 Environmental performances of main thermal waste treatment processes

Flue gas treatment	Units	PYR/gas b	PYR/gas c	PYR d	Gas e	Gas f	Gas f	PYR f	PYR f	PYR f	COMB a	COMB f	2007/76/EC
Particulates	mg/Nm^3	<2	2	1	0.01	0.2	0.24	<0.05	<1	<0.5	<1	<1	10
SO_2	mg/Nm^3	<6	<1	20	17	<1	19.8	<0.7	<5	<1.5	20	<5	50
NO_x	mg/Nm^3	<45	<37	167	128	<10	42	<70	<10	<50	<200	<80	200
CO	mg/Nm^3	<6	<2	<10	0.1	<3	<2	<2.3	<5	<8	<5	<10	50
HCI	mg/Nm^3	<1.5	2	5	1.2	<0.2	3.61	<0.5	<0.5	<0.5	7	<1	10
HF	mg/Nm^3	<0.15	<0.1	–	0.0082	<0.1	<0.09	<0.05	<0.1	<0.1	<0.2	<0.1	1
TOC	mg/Nm^3	<1.5	<1	1.6	1	2	<0.2	<1	1	<0.5	<3	<2	10
Hg	mg/Nm^3	<0.01	0.006	0.011	0.0001	0.007	0.00327	0.006	<0.006	<0.001	0.004	<0.001	0.05
Cd/TI	mg/Nm^3	0.0002	0.006	0.006	0.001	<0.002	0.00002	<0.002	<0.0035	<0.001	<0.001	<0.001	0.05
Heavy metals	mg/Nm^3	0.01	0.006	0.054	0.024	<0.04	0.00256	<0.05	<0.04	<0.006	<0.2	<0.05	0.5
PCDD/F	ng ITEQ/ Nm^3	0.0005	0.003	0.001	0.0009	<0.02	0.0008	<0.005	<0.01	<0.01	0.03	<0.05	0.1

a: Spray absorber, fabric filter (with lime and activated carbon), SNCR

b:Wet scrubbing (4 stages), fabric filter (with sodium bicarbonate), SNCR/SCR

c: Fabric filter (with sodium bicarbonate), SCR

d: Lime with feed, fabric filter (with sodium bicarbonate and activated carbon), SNCR

e: Flue gas recirculation

f: Unknown

of some improvements in particular for NO_x and particulate emissions, because very low emission levels can be obtained by means of less performing treatments.

As one can easily understand from the reported remarks, the emissions of direct combustion of waste and pyrolysis/gasification and combustion of syngas (for the composition see Table 9) in industrial boilers are quite similar due to the technological performances of modern treatment devices adopted for incineration (fabric filters, selective non catalytic reduction (SNCR)—selective catalytic reduction (SCR), activated carbon and so on).

Pyrolysis/gasification could give better environmental results if compared to direct combustion [32] when syngas is recovered in a gas engine equipped with SCR and catalytic oxidation. In this case, the waste gas flows and the pollutants mass flows could be appreciably lower, as reported by Table 10. As far as pyrolysis/gasification is concerned, the emissions have been assumed on the basis of performances that can be met by modern gas engine equipped with Best Available Techniques (BAT). The energy data of the configurations come from figures reported by Table 7, that is site power use is not considered. On the basis of the reported assumptions, pyrolysis/gasification of waste and the use of gas engine seems to allow lower emissions, in particular for particles and NO_x (besides heavy metals and PCDD/F for the same reasons reported in the previous chapters). Total organic carbon could be emitted at higher level from the gas engine, up to 600 mg/Nm^3, but it can be strongly reduced by means of thermal oxidation.

Table 9 Syngas composition

% Volume wet gas	
CO	8.79
H_2	8.61
CH_4	6.51
C_2H_2	0.90
C_2H_4	3.10
C_6H_6	0.88
CO_2	16.50
H_2O	9.48
N_2	45.13

From the point of view of the flue gas volume, as more or less previously indicated, it is necessary to highlight that the gasification processes produce flue gas volumes certainly lower in comparison with the flue gas volume derived from an incineration process; this is due to the intrinsic characteristics of the process. In fact, while for the combustion operating in an incinerator, a substantial excesses of air is required, gasification processes operate in presence of a quantitative of oxidizing agent lower than the stoichiometric.

Anyway in account of the consideration that the main fate of syngas remains the combustion in a boiler with

Table 10 Energy and environmental performances

	Combustion	PYR/ gasification
RDF input (kg/h) lhv = 3,600 kcal/kg	956	885
Thermal input (kW)	4,000	3,704
Overall gross electrical efficiency (%)	25	27
fuel utilization (%)	25	58
power OUT (kW)	1,000	1,000
thermal OUT (kW)	0	1,148
WASTE GAS (Nm^3/t RDF dry O_2 referred)	6,510 ($O_2 = 11$ %)	4,069 ($O_2 = 5$ %)
particulates (mg/Nm^3 O_2 referred)	10	1
NOx (mg/Nm^3 O_2 referred)	200	100
CO (mg/Nm^3 O_2 referred)	50	50
TOC (mg/Nm^3 O_2 referred)	10	150
particulates (g/t RDF)	65	4
NO_x (g/t RDF)	1.302	407
CO (g/t RDF)	326	203
TOC (g/t RDF)	65	610

steam production, it is necessary the addition of air downstream of the syngas production.

So, in both case (incineration and gasification) the amount of flue gas that must be treated downstream of the energy recovery is more or less the same (as is evident from Table 11) in terms of volume produced per ton of waste treated (Table 11).

Conclusions

Gasification and pyrolysis technologies represent a very promising option for the thermal treatment of MSW. On the other hand there are still few relevant operational plants and therefore little full scale operation data upon which developers and policy makers can rely. The uncertainties (regarding performance, reliability and economics) associated with using pyro-gasification must be generally considered to be high.

A real advantage of the innovative technologies applied to MSW is their modular design: small units can be added to or taken away as waste streams or volumes change, and are therefore more flexible and can operate at a smaller scale than mass-burn incinerators. The modular design allows a greater degree of flexibility in terms of location: plants can be built where they are necessary and designed as needed. This aspect allows a significative advantage during the phase of plant location because of the more simple acceptance from the local communities and the reduction in costs and in environmental impact due to the waste transport.

Table 11 Incineration–gasification volumes comparison

Incineration dry flue gas volumes ($O_2 = 11$ %) (Nm^3/t RDF)	6,000–7,000
Incineration stoichiometric waste dry gas volumes ($O_2 = 0$ %) (Nm^3/t RDF)	3,000–3,500
Gasification dry flue gas volume ($O_2 = 11$ %) (Nm^3/t RDF)	5,500–7,000
Gasification wet syngas volumes (air–gas) (Nm^3/t RDF)	1,500–3,500

To summarise collected data about gasification, pyrolysis, plasma gasification and mixed processes, it arises that:

- gasification can be considered a really competitive technological alternative to incineration for the energetic valorization of the MSW;
- pyrolysis has been demonstrated to operate satisfactorily on specific feed material, like industrial waste, but today it doesn't constitute a complete alternative to the incineration of MSW: the main problem remains the bottom solid residue (char): that contains significant amounts of carbon. The char could be used as coal replacement or as a gasifier feedstock (for systems based on the combination of pyrolysis and gasification);
- plasma torch can't be considered suitably proven due to a lack of adequate references on MSW treating.

As far as energy efficiency is concerned, direct combustion of MSW seems to grant higher power productions if compared to syngas recovery by means of industrial boilers or gas engines, in consideration of pre-treatment consumptions and parasitic loads, as well as of higher thermal conversion efficiency of direct combustion. Only co-firing of syngas in large power plants or the use of combined cycle gas turbine might give better energy efficiency results; the use of gas engine and gas turbine for syngas recovery could allow very good fuel utilization rates; the use of thermal energy can strongly improve the environmental impact of plants, by displacing existing fossil fuel energy plants.

With regards to air emissions, plants based on all the technologies in connection with a conventional steam boiler and steam turbine cycle can largely meet the emissions limits; syngas combustion could grant lower concentrations for heavy metals and PCDD/F. Considerably lower NO_x and particles emissions can be obtained for gasification when syngas is recovered by BAT equipper gas engines.

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